Outline

- LEAP results on Nitronex devices
  - Characterization of gate/epilayer interfacial layer
- Challenges with performing LEAP
  - LEAP results on AFRL devices
    - Sample fracture during LEAP
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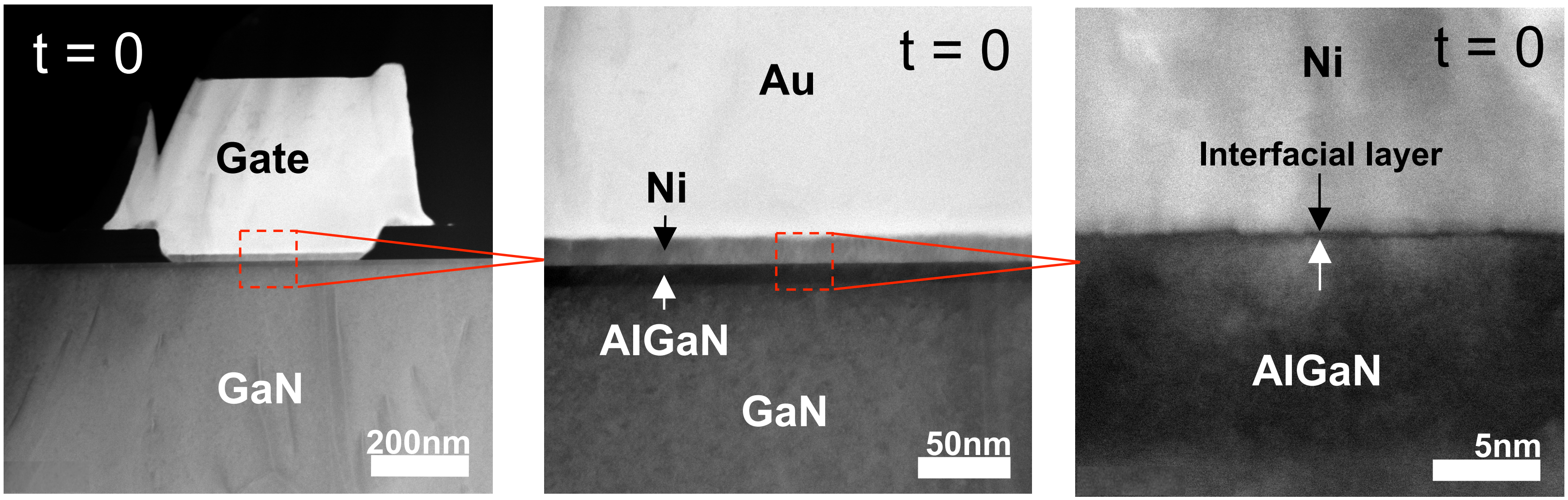
  - Dr. Hono's group (University of Tsukuba, Japan)
- Conclusions and future work

TEM of Gate/Epi-layer Interface (Nitronex)

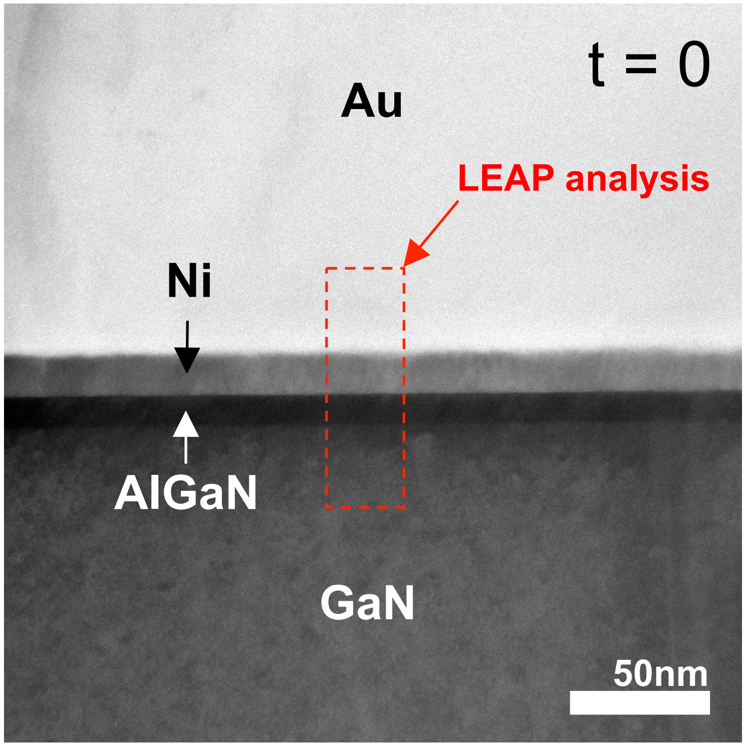
<u>HAADF-STEM Images</u>



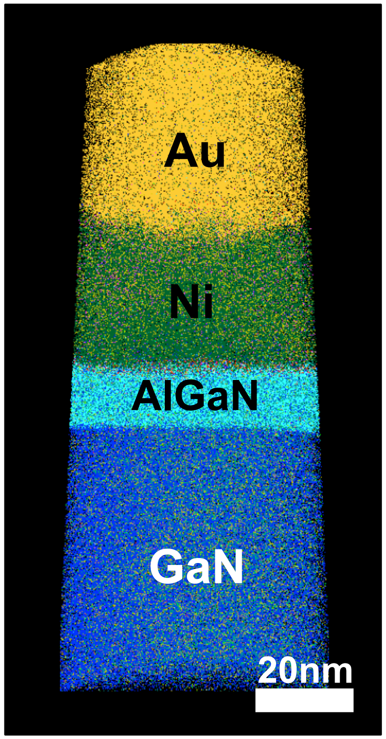
- Interfacial layer ~0.5 nm-thick evident between Ni and AlGaN; can perform LEAP to determine composition

LEAP of Gate Stack and Epilayers (Nitronex)

HAADF-STEM

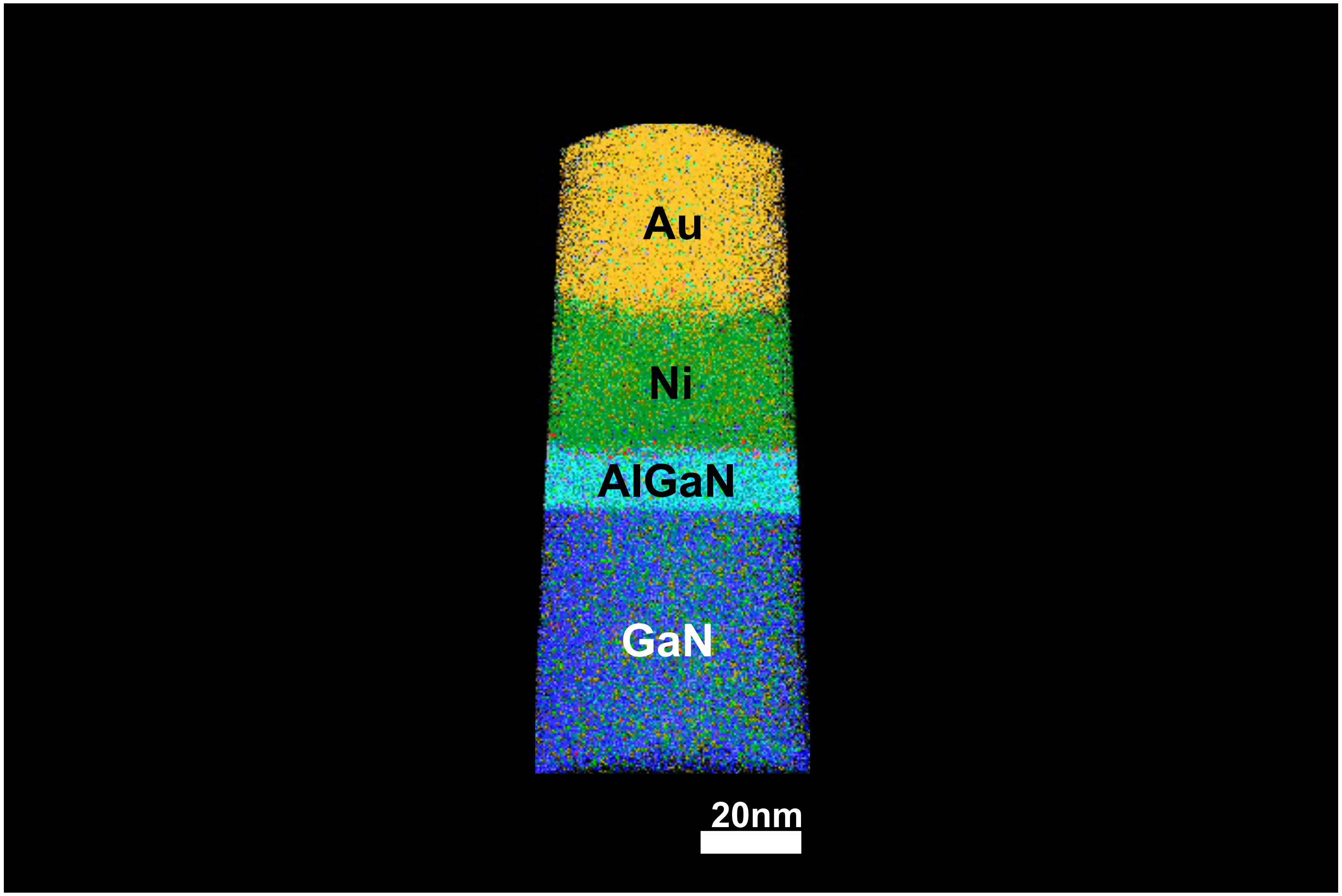


LEAP



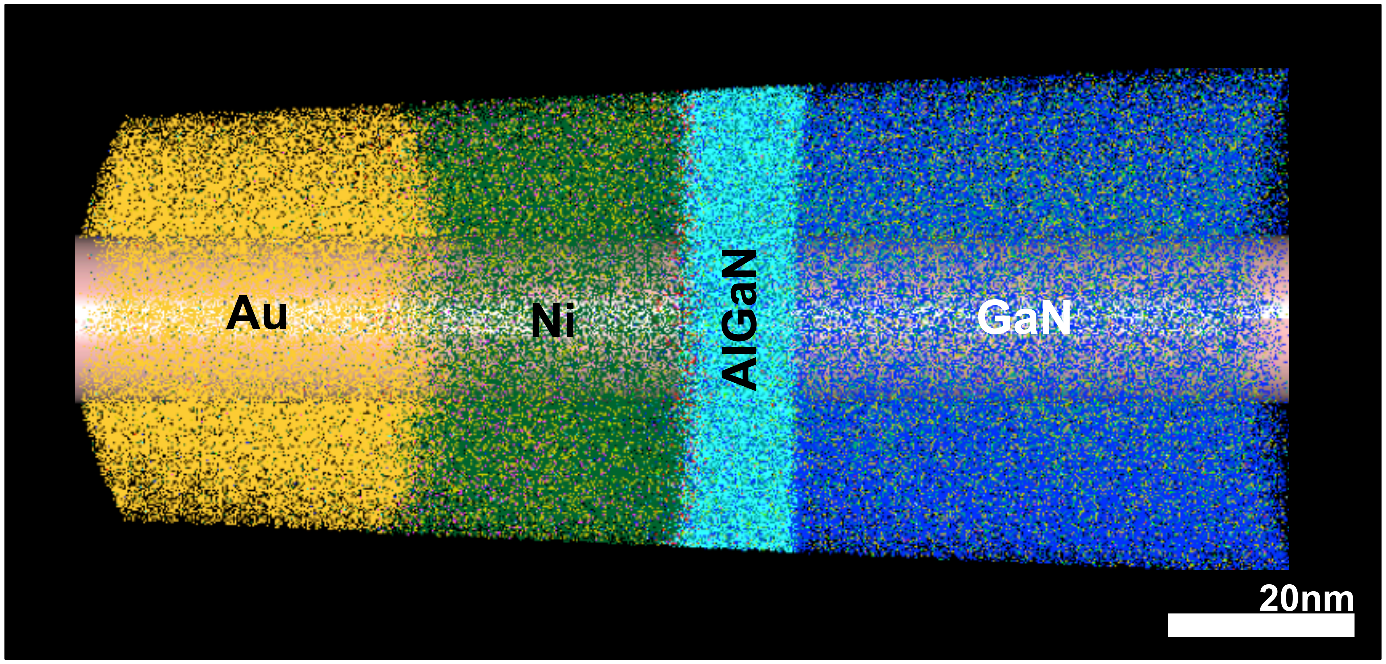
- Gate metal stack, gate/epilayer interface, AlGaN/GaN interface contained in LEAP reconstruction

LEAP Reconstruction Movie (Nitronex)



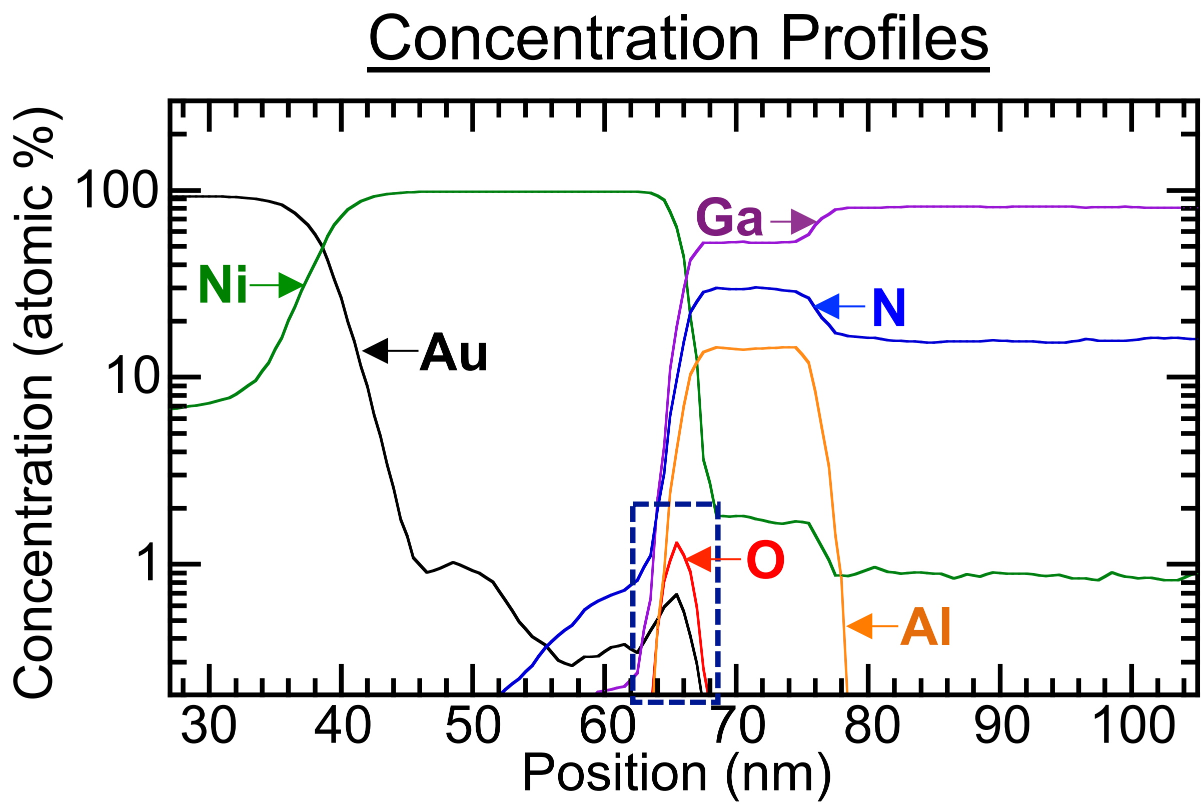
Analysis Cross Section (Nitronex)

LEAP reconstruction showing all atoms



- Position a “data pipe” orthogonal to the layers to produce 1D concentration profiles for each species

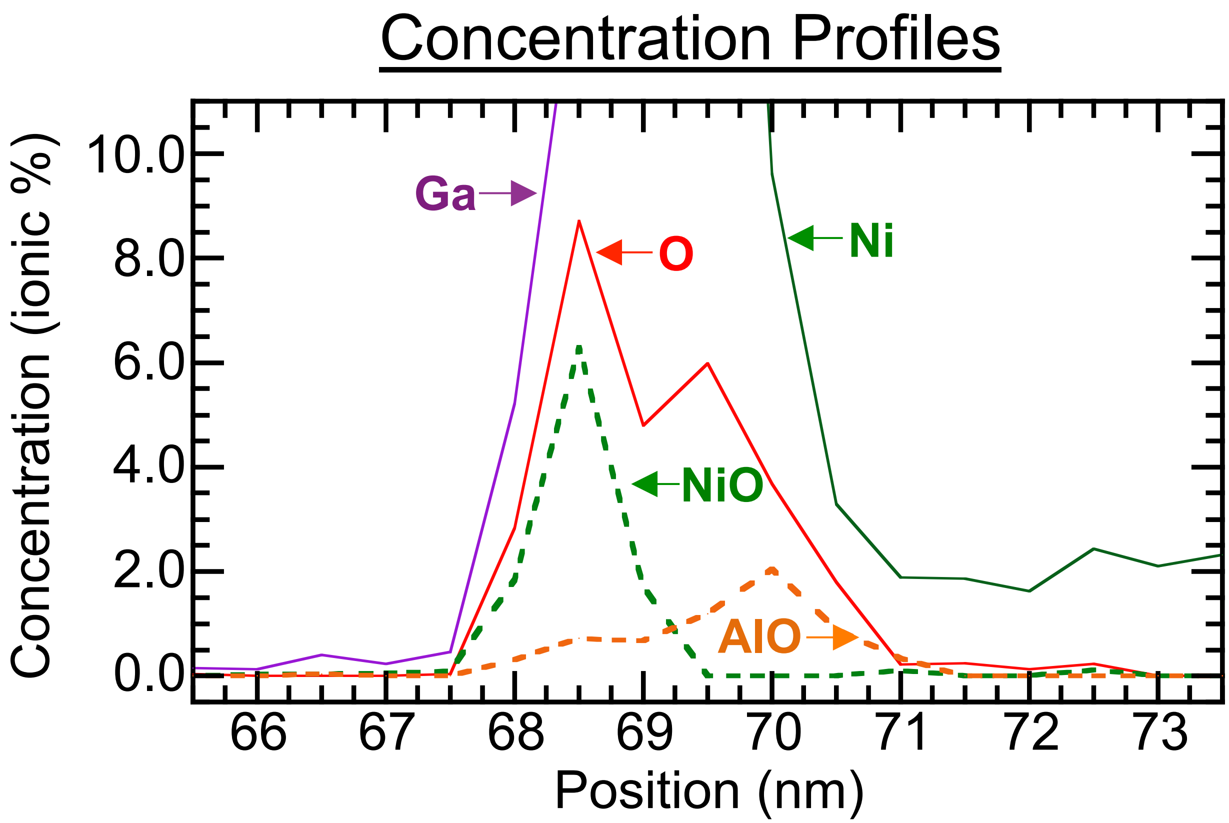
1D Interface Concentration Profiles (Nitronex)



- Perform closer examination of the Ni/AlGaN interface to characterize interfacial layer

M.R. Holzworth, *et al.*, Appl. Phys. Lett. **98**, 122103 (2011).

A Closer Inspection of the Interface (Nitronex)

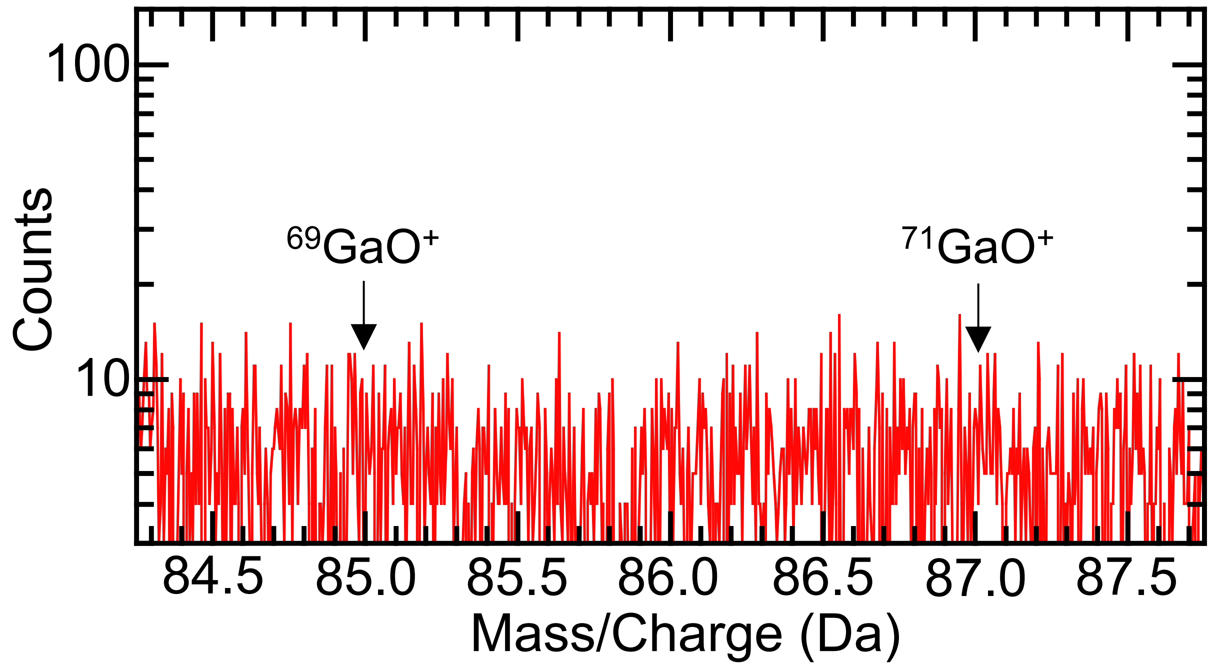


- Interfacial layer composed of distinct NiO_x and AlO_x layers, but what about GaO_x?

M.R. Holzworth, *et al.*, Appl. Phys. Lett. **98**, 122103 (2011).

Is GaO_x Present in the Interfacial Layer? (Nitronex)

Partial Mass/Charge Spectrum

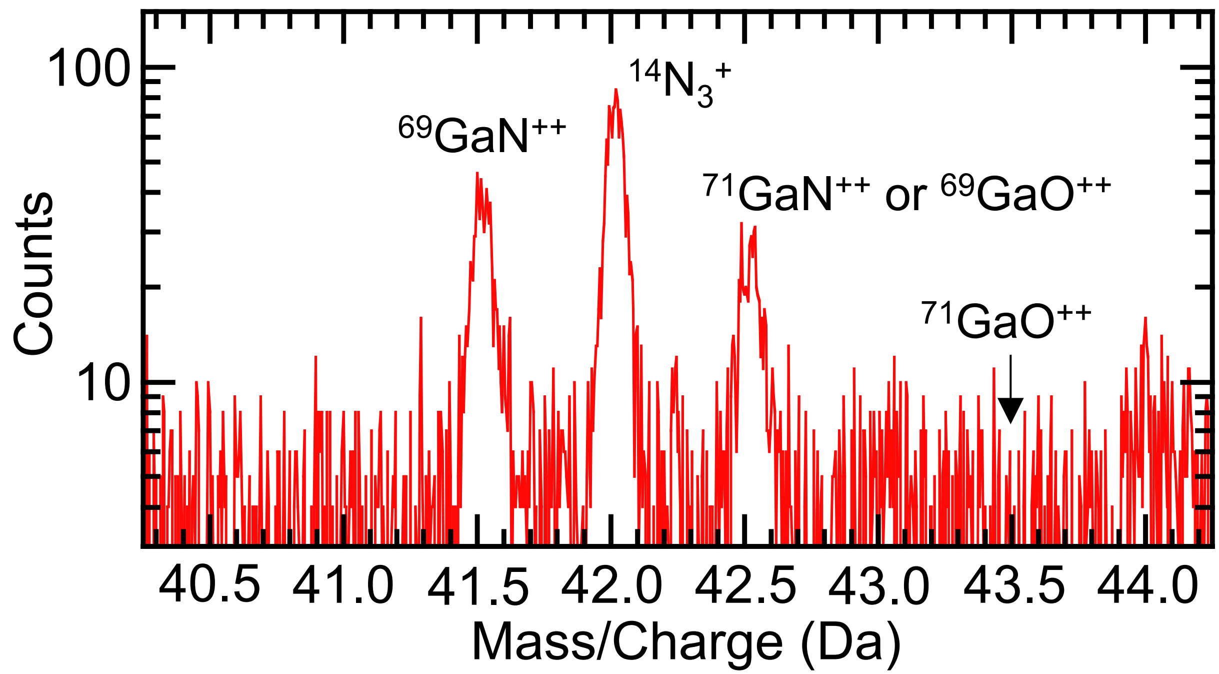


- Expect peaks at 85.0 and 87.0 for GaO, but none observed; should also look at 42.5 and 43.5 for doubly-ionized species

M.R. Holzworth, *et al.*, Appl. Phys. Lett. **98**, 122103 (2011).

Is GaO_x Present in the Interfacial Layer? (Nitronex)

Partial Mass/Charge Spectrum



- $^{69}GaN^{++}/^{71}GaN^{++}$ = 1.52±0.05 (close to $^{69}Ga/^{71}Ga$ = 1.51) and lack of peak at 43.5 indicate no GaO_x present

M.R. Holzworth, *et al.*, Appl. Phys. Lett. **98**, 122103 (2011).

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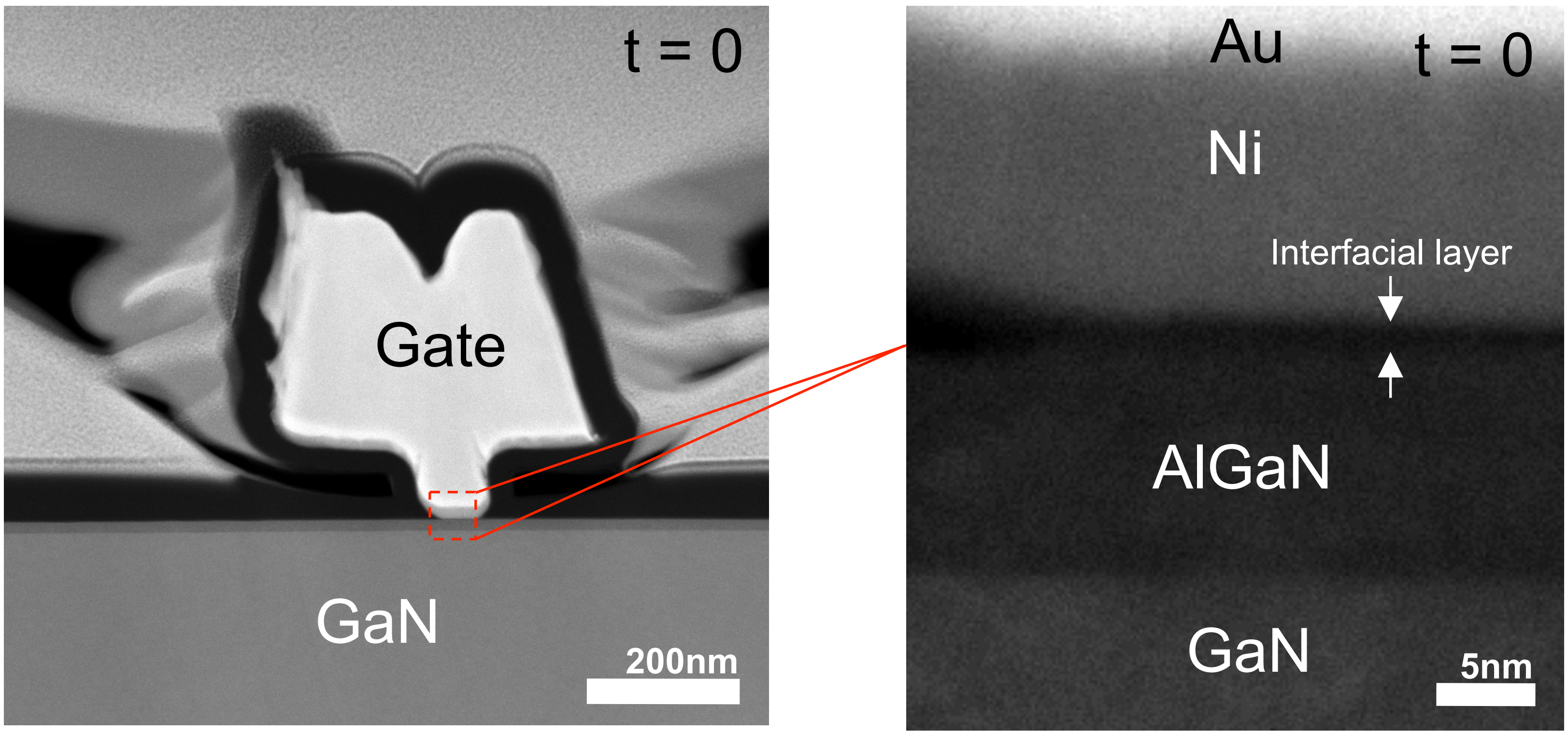
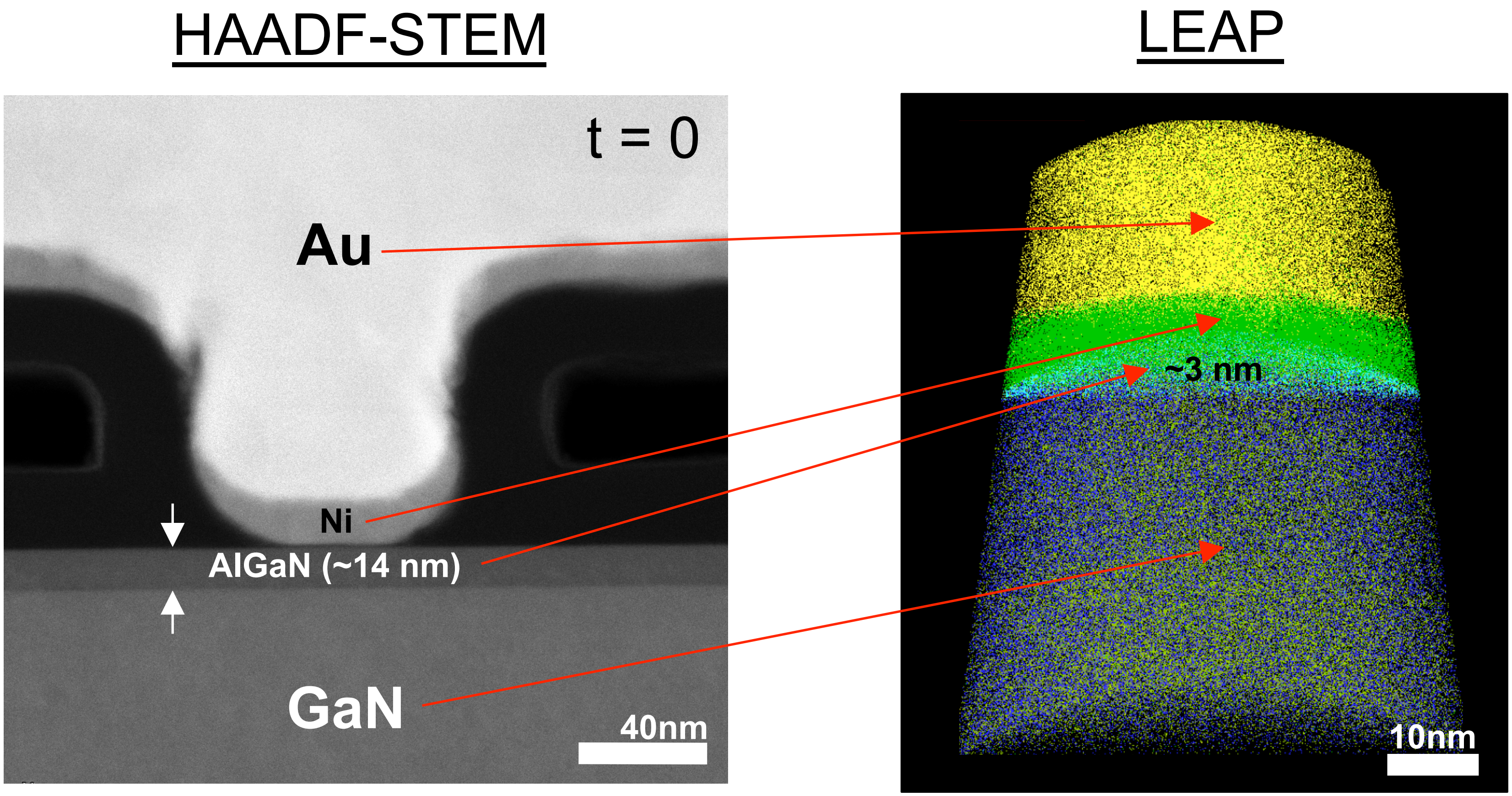
TEM of Gate/Epi-layer Interface (AFRL)

<u>HAADF-STEM Images</u>



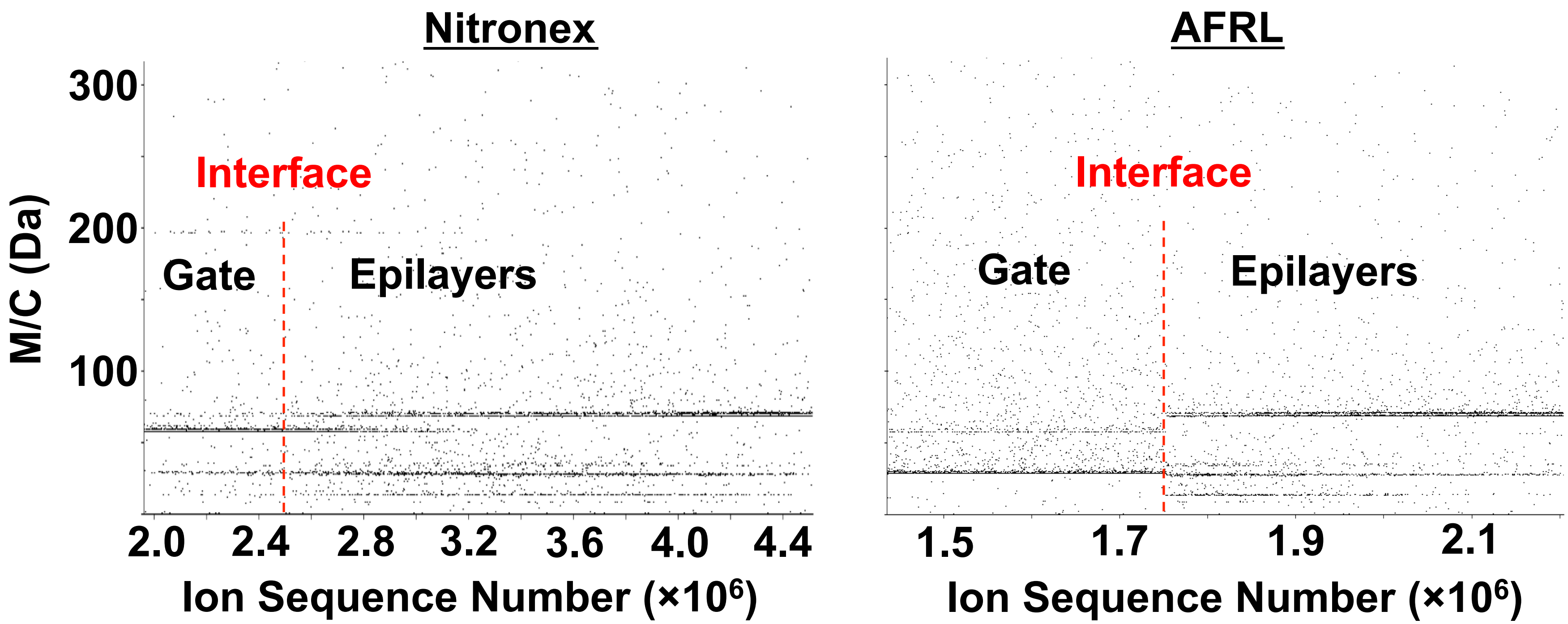
- Interfacial layer ~1.5 nm-thick present in AFRL devices; attempted LEAP analysis to determine composition

LEAP of AFRL Devices



- Ni and AlGaN layers thinner in LEAP than observed in TEM; indicates fracture at Ni/AlGaN interface during LEAP

Mass/Charge History Comparison



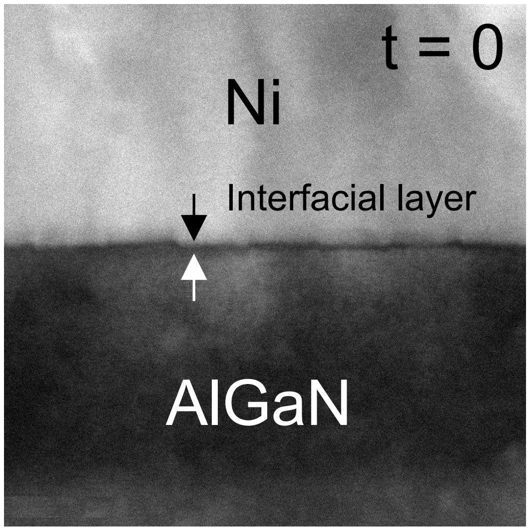
- Nitronex: M/C history broad and graded; indicates continuous evaporation without fracture
- AFRL: M/C history shows sharp discontinuity at interface; indicates tip fracture at gate/epilayer interface

Limitations of LEAP for Analyzing Devices

- Fracture during LEAP analysis of ARFL and TriQuint devices occurs near interfaces
- Possible explanations for fracture at interfaces
  - Weak interfacial adhesion
  - Interfacial layer thickness
  - Stresses generated during laser pulsing
  - Gate morphology (cracks)
- LEAP was successful on Nitronex, but not AFRL or TriQuint devices, so what is inherently different?

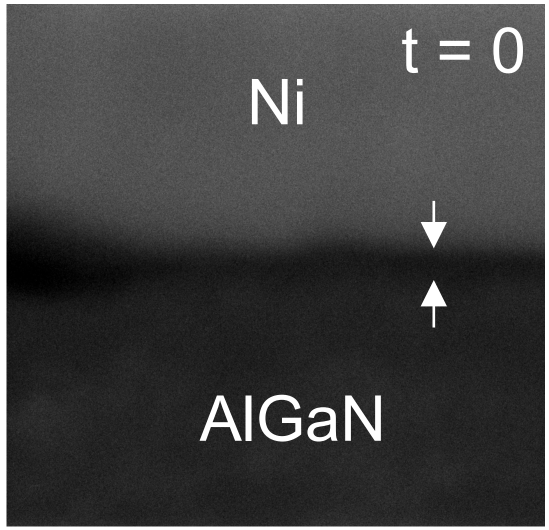
Differences in Interfacial Layers Between Devices

Nitronex



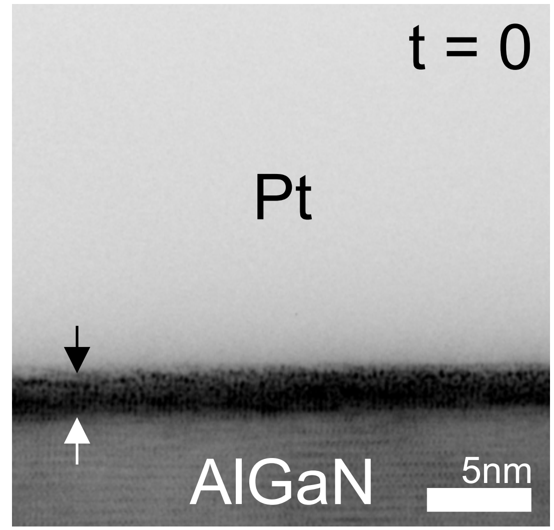
~0.5 nm

AFRL



~1.5 nm

TriQuint

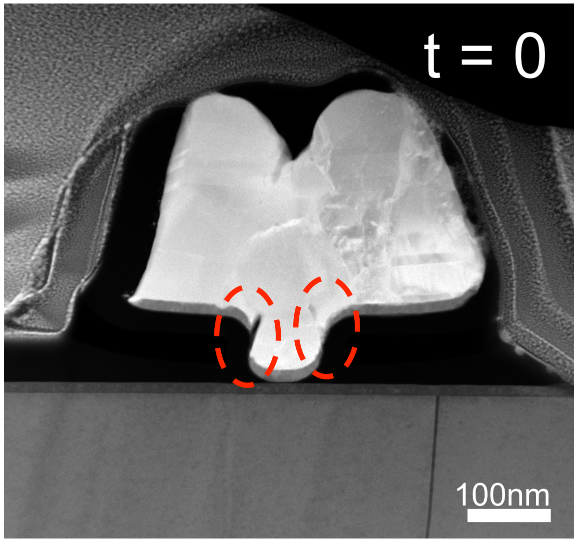


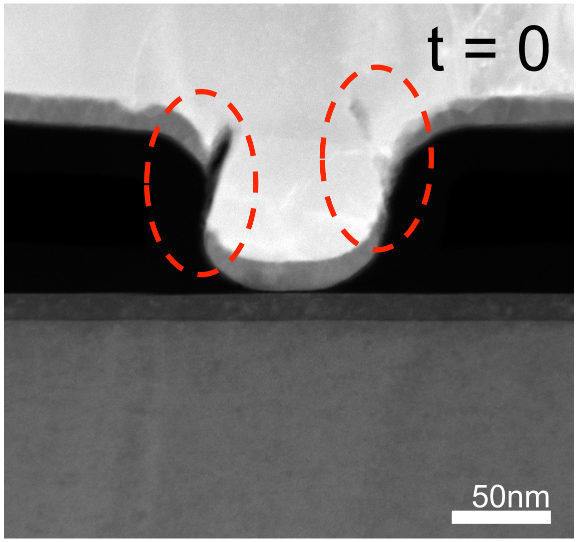
~1.8 nm

- Nitronex HEMTs have smallest interfacial layer; these were the only devices that didn't fracture during LEAP analysis

Gate Morphology Effects: Cracks (AFRL)

HAADF-STEM Images





- Current atom probe samples employ top-down serial sampling method: Au ➔ Ni ➔ AlGaN ➔ GaN
- Cracks in the gate contacts could cause fracture during LEAP analysis (just a speculation)

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Addressing LEAP Challenges

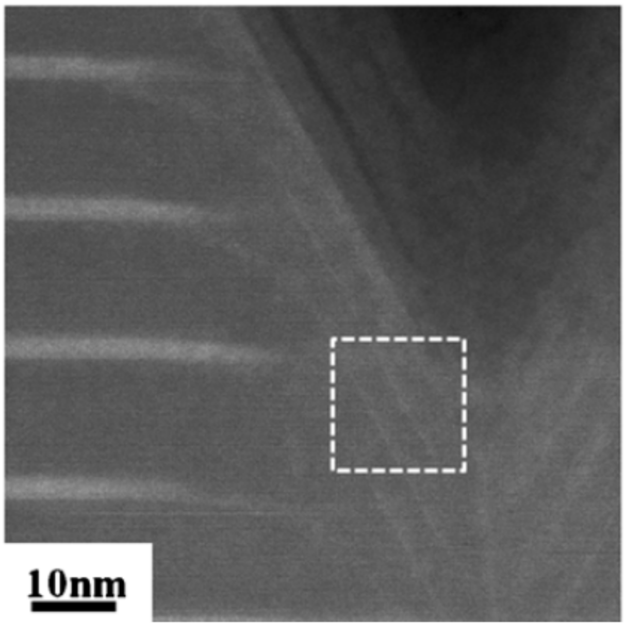
- Use APT systems with shorter wavelength lasers
  - LEAP limited to laser wavelength of 532 nm
  - Newer systems have wavelengths < 360 nm
  - Small wavelength = higher photon energy
- Small wavelength improves evaporation during APT
  - Direct excitation (bandgap < photon energy)
  - Thermal excitation (bandgap > photon energy)
    - Both result in enhanced tip conductivity, improved evaporation
- Recently established collaboration with short wavelength laser APT capabilities
  - Dr. Hono (University of Tsukuba, NIMS at MMU)

Atom Probe Collaboration

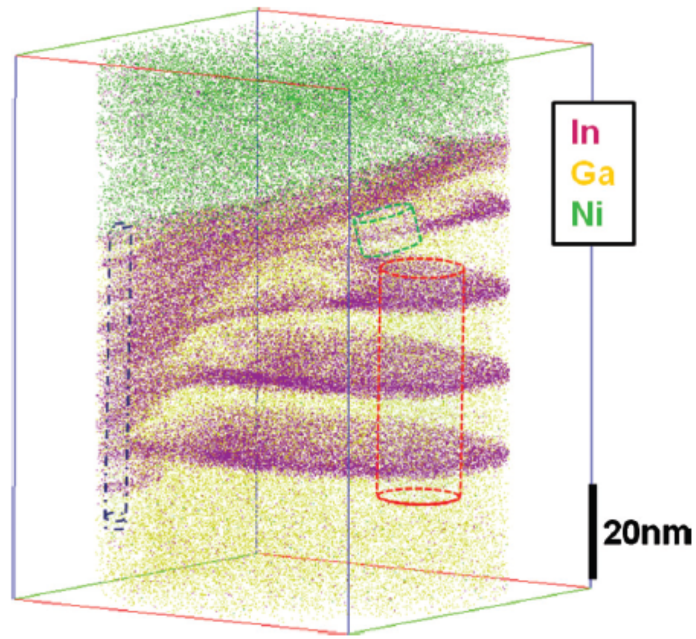
- Dr. Kazuhiro Hono
  - University of Tsukuba (Tsukuba, Japan)
  - NIMS & MMU (Magnetic Materials Unit)
- Custom built atom probe system
  - Four laser wavelengths: 1030, 515, 343, 258 nm
    - Wavelength for present work limited to 532 nm
  - Demonstrated APT results on insulating/ wide band gap materials
    - ZnO, MgO, $LiCoNiMgAlO_2$ (Li-ion battery)
    - InGaN/GaN Quantum Wells
- Ray currently in Japan working w/ Hono's group

Some Results from Hono's Group

HAADF-STEM



APT Reconstruction



- Hono's APT system capable of analyzing InGaN/GaN multi-quantum well structures (similar to HEMT materials)

S. Tomiya *et al.*, Appl. Phys. Lett. **98**, 181904 (2011).

Conclusions

- 0.5 nm-thick interfacial layer in Nitronex devices analyzed using LEAP
  - Identified as distinct NiO_x and AlO_x layers
  - GaO_x not present
- Difficulties analyzing AFRL and TriQuint devices
  - Thicker interfacial layers compared to Nitronex devices
  - Cracks in gates of AFRL devices
- Started collaboration with Hono's group
  - System may be effective with thicker interfacial layers
  - Samples must be made on-site for best results

Future Work

- Atom probe collaboration with Hono's group
  - Currently in progress
  - Analyze structure/composition of defects in AFRL devices
- Structure-composition relationships of defects
  - Provide insights into formation mechanisms
- Correlation of electrical degradation with defect structure, composition, etc.